On the Maturity of ArF Resists: When Can they be Implemented in Manufacturing?

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By Kurt Ronse, IMEC

History of ArF resists

The transition in optical lithography to a lower exposure wavelength usually requires the development of new photoresists. The transition from G-line (436nm) to I-line (365nm) was relatively easy compared to the transition from I-line to DUV (248nm), where the principle of chemical amplification was introduced. New problems like acid diffusion and resist contamination were observed and needed to be better understood and controlled before DUV resists became production worthy. This has taken some time and this was the main reason why DUV lithography was not introduced before the 0.25mm technology node. The transition from 248nm (KrF DUV) to 193nm (ArF DUV) lithography also requires a new resist chemistry, as will be explained in the next section. Also in this case, the availability of a mature 193nm resist, together with the availability of the required number of ArF exposure tools, is delaying the introduction of 193nm lithography to the 100nm technology node. Nevertheless, steady progress in resist performance is observed every quarter now. The currently observed resist performance (Figure 1), which already approaches the requirements for the 100nm technology node, creates confidence that 193nm lithography will be ready in time for introduction between the 130nm and 100nm technology nodes.

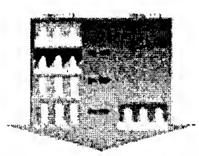

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Figure 1. Evolutionary progress in ArF resist performance.

Chemistry approaches for ArF resists

The requirements for high-performing 193nm resist materials include the following: adequate optical transparency at 193nm, good imaging properties, high etch resistance, high sensitivity (5-15mJ/cm^2), good adhesion properties as well as compatibility with a 2.38 wt% TMAH

aqueous base developer, etc.

As already mentioned, the high opacity of phenolic polymers (as used in 248nm resists) at 193nm precludes them from being used in single layer resist schemes at this wavelength, except in thin layer imaging schemes.

Thin layer imaging techniques (TLI) such as bi-layer schemes have several advantages over single layer resist and are especially attractive to be implemented for back-end applications[2]. Nevertheless, single layer resists have been the industry's preference and continued to be most widely used, which has led to major research efforts in the development of transparent single layer resist. These resulted in the discovery that polymethacrylates are highly transparent at 193nm; good imaging performance with acrylate based resists was first reported by researchers [3] at IBM and MIT Lincoln Labs. A serious limitation of these first acrylate resists was their poor dry etch resistance. Indeed, the major challenge in the development of single layer resists is to combine transparency and etch resistance into one material. A breakthrough came when acrylate polymers containing alicyclic pendant groups were reported[4] to have plasma etch resistance comparable to aromatic polymers. This finding prompted many researchers to incorporate alicyclic units and acid labile ester functionality into polymethacrylates as pendant group. This type of resist design is classified as the acrylate (methacrylate) platform.

Another approach[5-7] is to incorporate the alicyclic structure into the polymer backbone itself. These so-called cyclo-olefin polymers have the necessary transparency and offer the possibility of even higher etch resistance but have some drawbacks such as severe hydrophobicÒty causing poor adhesion. The dissolution and adhesion properties of the cyclo-olefin polymers can be controlled and optimized by the incorporation of acidic and polar groups into the cyclo-olefin structure.

Today's 193nm resists are based on three main chemical platforms (Figure 2): the methacrylate copolymers with alicyclic pendant groups, cycloolefin polymers (CO) and alternating copolymers of cycloolefins with maleic anhydride (COMA). All of the present commercial available resists are based on one of these three classes or are hybrids[6] thereof.

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Figure 2. Chemical platforms for 193nm resists.

Each of the 193nm resist platforms have their specific strengths and weaknesses.

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The methacrylate type resist systems with alicyclic pendant groups are made via a straightforward polymerization process with good control. The acrylic materials are quite transparent at 193nm, have excellent adhesion properties and demonstrate high resolution, but have limited etch resistance. Acrylic materials suffer from high line edge/sidewall roughness and significant linewidth slimming during SEM inspection (see below). The acrylate type resists are also more susceptible to pattern collapse due to their limited mechanical rigidity.

The cyclo-olefin (CO) type resists show excellent etch resistance, good transparency and high mechanical rigidity but have only moderate adhesion and somewhat lower resolution as compared to acrylate resists. A potential drawback of this CO platform is the use of metallic catalyst for the polymerization which could be an area of concern with regard to resin purity.

The COMA resists have good etch resistance, high mechanical rigidity and good resolution, but only moderate transparency.

Both CO and COMA platforms are less susceptible to pattern collapse and show less linewidth slimming during SEM inspection.

Imaging performance of ArF resists

Using the ASML PAS5500/950 step and scan system, installed in the IMEC pilot line and interfaced to a TEL Clean Track ACT8, very promising imaging results were obtained lately using the newest 193nm resists. The maximum NA of the PAS5500/950 is 0.63.

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Figure 3(a). 130nm equal lines and spaces through focus (experimental conditions: ASML PAS5500/950, 0.63 NA, annular illumination 0.8/0.5, 350nm resist thickness, binary mask).

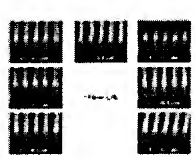

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Figure 3(b). 110nm equal lines and spaces through focus (experimental conditions:

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ASML PAS5500/950, 0.63 NA, annular illumination 0.8/0.5, 350nm resist thickness, binary mask).

Figure 3 shows the depth of focus obtained for (a) 130nm and (b) 110nm dense lines and spaces through focus, exposed using a binary mask and annular illumination. Figure 4 shows the depth of focus obtained for 100nm semi-dense lines, exposed using a binary mask and conventional illumination. Figure 5 shows the depth of focus of 130nm semi-dense and 140nm isolated contacts, exposed with an embedded phase shift mask.

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Figure 4. 100nm semi-dense lines (1:1.5 duty ratio) through focus (experimental conditions: ASML PAS5500/950, 0.63 NA, s = 0.65, 350nm resist thickness, binary mask).

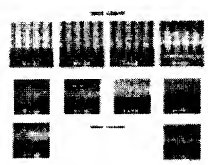

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Figure 5. 130nm semi-dense and 140nm isolated contacts through focus (experimental conditions : ASML PAS5500/950, 0.63 NA, s = 0.5, 400nm resist thickness, 6% embedded PSM).

Using more aggressive enhancement techniques, the resist performance can already be explored for real 100nm technology node dimensions. Figure 6 shows the depth of focus of 70nm isolated lines, exposed with an alternating PSM. The DOF is at least 0.8mm.

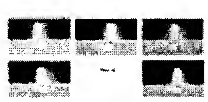

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Figure 6. 70nm isolated lines through focus (experimental conditions: ASML PAS5500/950, 0.63 NA, s = 0.3, 330nm

resist thickness, double exposure of alternating PSM with trim mask).

Extrapolation of the results to higher NA (as are expected to be introduced from 2001 onwards for volume manufacturing) holds promise for the 100nm technology node requirements.

Process integration challenges of ArF resists

Besides the excellent improvements in imaging quality, as illustrated in the previous paragraph, the ArF resists of course also have to fulfil other requirements before they can be integrated in manufacturing lines.

The dry etch resistance of ArF has so far been a major issue. COMA resists have recently shown improvements in etch resistance but are still far worse in etch resistance compared to I-line and state-of-the-art KrF resists. It is questionable whether ArF resists will ever reach the dry etch resistance of I-line or KrF resists. Integration choices will largely determine the success of ArF lithography in manufacturing processes. It has been shown (Figure 7a) that the use of an SiON hardmask instead of an organic ARC on critical 130nm and 100nm gate levels strongly reduces the requirement in resist thickness, and successful gate etch and strip was achieved using a 330nm thick ArF resist. After poly-Si etch, more than 100nm resist thickness remains.

The 130 and 140nm contacts, exposed in a 400nm thick resist, could also be etched into a typical oxide stack without consuming all the resist (Figure 7b).

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Figure 7(a). 130nm gate pattern, exposed on the ASML PAS5500/950 using a 330nm thick single layer resist on an SiON hard mask: (top) after litho; (middle) after etch; (bottom) after strip.td>

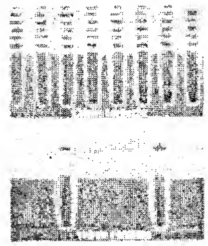

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Figure 7(b). 130nm semi-dense and 140nm isolated contacts after etch and strip (650nm oxide thickness).

Line edge roughness (LER) is another issue that has always been more pronounced for ArF resists[8]. Here the more recent resists are also exhibiting less line edge roughness. In recent work, it has been shown that the line edge roughness of the resist is only partially transferred into the polysilicon during etch. However, the resists with the lowest LER after litho exhibit the lowest LER after etch. Line edge roughness figures in the order of 4nm (3sigma) have been obtained after etch. This is comparable to the results of KrF resist etching and is not considered to be a show stopper for the 130nm and 100nm technology nodes.

Until recently another weak point of ArF resists used to be the linewidth sensitivity to the PEB temperature, which used to be twice as large compared to KrF resists. Further improvements can still be expected here. Nevertheless, improvements in hot plate technology (TEL PCH PEB module) have already resulted in excellent CD uniformity numbers (Figure 8). Also, the day-to-day dose stability, as measured daily over a period of 3 months, resulted in a 3s of 0.4mJ/cm^2 (on a dose to size of 7 mJ/cm^2) indicating the improved stability of ArF resists. In both cases, no attempt was made to correct for CD metrology repeatability errors.

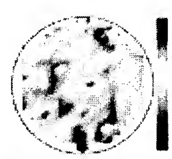

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Figure 8. Intra-wafer CD uniformity for 130nm isolated lines, printed across a 200mm wafer (3s = 3.9nm, range 7.0nm).

When integrating 193nm resists in various critical layers, problems were encountered with adhesion of several resists, mainly on inorganic substrates. Special care has to be taken in priming the wafers and pretreating the substrates in order to avoid adhesion problems. As expected, fewer problems were encountered with acrylate resists.

Finally, it is well known that ArF resists tend to shrink under SEM inspection. Here, improvements are also observed in resist chemistry (Figure 9) where COMA resists are clearly less sensitive than acrylate resists. Furthermore, CD SEM manufacturers are working on the low voltage conditions in order to reduce this effect. The challenge is to obtain similar image quality and measurement repeatability with lower electron doses.

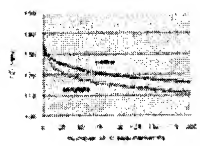

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Figure 9. CD shrinkage with two types of ArF resists under multiple measurements.

Conclusions and outlook

In this paper, the recent progress and current status of ArF resists has been outlined. An overview of the various resist platforms under development has been given. Although high NA ArF step and scan systems for volume production are not yet available, it has been shown that the imaging performance of the latest resists start to fulfil the requirements for the 100nm technology node. Several integration issues of nowaday's ArF resists have been discussed (dry etch resistance, line edge roughness, adhesion, CD shrinkage under SEM inspection). Although further improvements are expected here and there, it has been shown that most of the issues could be dealt with by making clever integration choices.

In conclusion, the authors are convinced that the steady progress in ArF resists every six months is sufficient to meet the volume manufacturing requirements from 2002 onwards.

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Kurt Ronse received a M.S. Degree and PhD in Electrical Engineering from the University of Leuven (Belgium). He joined the lithography group in IMEC in 1990, specializing in the field of phase shifting masks, off-axis illumination techniques and CD control optimization for 365nm and 248nm lithography. He has authored and co-authored over 60 publications and conference contributions in the field of optical lithography, and is member of the technical program committee of several international lithography conferences. He has been project leader in several European projects under the Esprit, Jessi, IST and Medea framework. Currently, he holds the position of lithography department director at IMEC. His main responsibility is the project management of a worldwide 193nm and 157nm lithography development program.

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It is well known that the continuous downscaling of device feature sizes results in a massive increase of lithography investment costs. Especially, the transition to a lower wavelength is an important cost factor: not only are the tools very expensive, but also a lot of manpower and wafer lot-turns are required to develop the new resist processes. Moreover, these new materials are typically less mature than those of the previous lithography wavelength technology. Therefore, the possibility to extend the available fab tools for future device dimensions is always an important consideration, and should be investigated.

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